A Low NOx Lean-Direct Injection, Multipoint Integrated Module Combustor Concept for Advanced Aircraft Gas Turbines

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Abstract

A low NOx emissions combustor has been demonstrated in flame-tube tests. A multipoint, lean-direct injection concept was used. Configurations were tested that had 25- and 36-fuel injectors in the size of a conventional single fuel injector. An integrated-module approach was used for the construction where chemically etched laminates, diffusion bonded together, combine the fuel injectors, air swirlers and fuel manifold into a single element. Test conditions were inlet temperatures up to 810 K, inlet pressures up to 2760 kPa, and flame temperatures up to 2100 K. A correlation was developed relating the NOx emissions with the inlet temperature, inlet pressure, fuel-air ratio and pressure drop. Assuming that 10 percent of the combustion air would be used for liner cooling and using a hypothetical engine cycle, the NOx emissions using the correlation from flame-tube tests were estimated to be less than 20 percent of the 1996 ICAO standard.

Introduction

Based on analysis of production of emissions worldwide, aviation contributes a small percentage of the total. However, the effect of aircraft emissions is magnified because they are emitted in concentrated regions near airports and traffic routes, and at altitude in the atmosphere (refs. 1 and 2). To ensure that the next generation of aircraft are as clean as possible, one of the NASA goals is to reduce emissions of future aircraft by a factor of three within ten years and a factor of five within 20 years.

The major effects of emissions from aircraft gas-turbine exhaust are to produce ozone and smog at ground level; to produce ozone, acid rain, contrails and cirrus clouds in the troposphere; and, for supersonic flight in the stratosphere, a reduction in the protective ozone layer (ref. 1). The nitrogen-oxide emissions, NOx, play a major role in all of these effects except for generation of contrails and cirrus clouds. Although an increase in overall engine efficiency, from higher engine pressure ratio, decreases the emission of the greenhouse gases CO_2 and H_2O, it also increases the NOx emissions. The purpose of this paper is to describe a method to reduce oxides of nitrogen (NOx) emissions that may be applicable to a wide range of engines and pressure ratios.

NOx formation on the lean side of stoichiometry is essentially an exponential function of flame temperature. The key to ultra-low NOx production is to burn therefore at the lowest possible flame temperature. This is equivalent to burning as lean as possible and with as uniform a mixture as possible to

avoid locally stoichiometric zones which produce high amounts of NOx. Lean-premixed-prevaporized (LPP) combustion satisfies these criteria and is commonly used in ground- power applications with great success in reducing NOx emissions. However, for an aircraft application there are concerns with auto-ignition and flashback in the premixing zones because of the higher pressures and temperatures and wide ranging duty cycle associated with aircraft engines. Also, LPP systems are susceptible to acoustic instabilities, which is a major problem in ground-power applications.

An alternative to LPP schemes is lean-direct injection (LDI) combustion. An LDI system differs from an LPP system in that the fuel is injected directly into the flame zone and thus does not have as great a potential for auto-ignition or flashback. However, as the fuel is not premixed and prevaporized, it is important to achieve fine atomization and mixing of the fuel and air quickly and uniformly so that flame temperatures are low and NOx-formation levels near those of LPP systems. The potential for low-NOx LDI combustors has been demonstrated by Anderson (ref. 3), Alkabie and Andrews (ref. 4), Shaffar and Samuelson (ref. 5), Terasaki and Hayashi (ref. 6), Tacina (ref. 7). They have shown that NOx emissions from an LDI combustor can approach those of LPP combustors.

The LDI concept described in this report is a multipoint fuel-injection/multi-burning zone concept. Each of the multitude of fuel injectors has an air swirler to provide quick mixing and a small recirculation zone for burning. The multipoint injection provides quick and uniform mixing, and the small multi-zone burning provides shorter burning residence time, both resulting in low-NOx formation. An integrated-module approach is used for construction where diffusion bonded, photo-chemically etched laminates combine the fuel injectors, air swirlers and fuel manifold into a single module (ref. 8). This module has 36-fuel injection sites, fuel-air mixing zones and burning zones, compared to the single large burning zone of a conventional combustor.

In this paper emission measurements are reported, made with a single module, in a 76-mm square flame-tube with uncooled thick ceramic cast walls. The test conditions are inlet pressures up to 2760 kPa, inlet temperatures up to 810K and flame temperatures up to 2100K. A correlation is developed relating the NOx emissions with the inlet pressure, inlet temperature, fuel-air ratio and pressure drop.

Configurations

The basic configuration consists of 25 or 36 fuel injectors equally spaced in a square pattern on a 76-mm square test section. Each fuel injector is a simplex fuel nozzle that is chemically etched into a flat metal plate to form an array of injectors. The fuel-injector system consists of plates that contain the fuel manifold, a plate to distribute the fuel to each injector, a plate with the simplex fuel injectors and, in the case of the 36-point injector, a plate with an air gap that provides thermal protection to the fuel. The plates that make up the fuel-injector assembly are diffusion bonded to form an integral assembly. The fuel-injector assembly is followed downstream with an air-swirler assembly of diffusion-bonded plates that have radial air-swirler geometry chemically etched into them. The fuel-injector array and air-swirler array are separate so that the air swirlers can be interchanged with swirlers of different swirl angle to evaluate the effect of intensity of air swirl on combustor performance. A drawing of the assembly is shown in figures 1 and 2, and photographs of the 25-point assembly is shown in figure 3.

Configurations

Number of Fuel Injectors	Configuration	Symbol	Swirl Number	Swirl Direction
25	A	▽	0.5	All same direction
25	B	O	0.5 and 0.8 combination	All same direction
25	C	■	0.8	All same direction
25	D	▲	0.5 and 0.8 combination	Alternating direction
36	E	◉	0.5 and 0.8 combination	All same direction

Experimental Facility

A schematic of the experimental facility is shown in figure 4. The incoming combustion air is heated by a nonvitiated heat exchanger to a maximum temperature of 840 K at a maximum pressure of 3000 kPa. The air flow is measured by a venturi flow meter, and fuel flow rate is measured by a turbine flow meter. The fuel-injector module is mounted in a stainless steel pipe with a 152-mm inside diameter. The fuel-air mixture is injected into a flame-tube that has a square cross section 76 mm on a side. The flame-tube flow passage is made of Zirconium oxide (ZrO_2), 12 mm thick, that is housed in a 152-mm-diameter pipe. The gap between the zirconium oxide tube and the pipe is filled with an alumina (Al_2O_3) casting. A water coil cools the outside of the pipe. The test section is 300 mm long, followed by a water–quench section and back-pressure valves. Gas sampling is done 203 mm from the fuel-injector exit with a single-hole, water-cooled probe in the center of the stream. There are single-hole traversing probes located at 102 and 152 mm from the fuel-injector exit for radial-profile measurements. The concentrations of O_2, CO, CO_2, HC (as total unburned hydrocarbon), NO, and NOx are measured by standard gas analysis procedures: chemiluminescence for NO, nondispersive infrared absorption for CO and CO_2, flame ionization for HC, and paramagnetic analysis for O_2. The $NO_2 \rightarrow NO$ converter is calibrated using standard NO_2 to verify that conversion efficiencies are greater than 96 percent. The precision error of the gas-sample measurements is estimated to be ±5 percent. This is based on the repeatability of data when the same configuration is tested on different days and with at least one change of configurations is made between tests.

Results and Discussion

The NOx emissions are plotted versus the adiabatic flame temperature for the 25- and 36-point modules in figure 5 at various test conditions. The NOx values are given in terms of emission index, g-NO_2/kg-fuel, where the emissions of NO are calculated as NO_2. Although the measurements for the individual figures are taken at the same nominal inlet conditions, they are corrected for small differences by the following factors: $(P_3 plot / P_3 actual)^{0.59}$, $\exp(.0052(T_3 plot - T_3 actual))$, and $(\Delta P plot / \Delta P actual)^{-0.56}$, where "plot" refers to the condition labeled in the plot and "actual" refers to the actual measured condition of the test. These correction factors are based on the correlation by Wey (ref. 9). All the NOx data are plotted at conditions where the combustion efficiency is greater than 99.9 percent. The adiabatic flame temperature is determined from the inlet conditions and the gas-sample fuel-to-air ratio. The NOx emissions for these plots are from the probe located 203 mm downstream of the fuel-injector face. The fuel-air ratio as determined by the emissions measurement is compared to the metered fuel-air ratio and generally is within 10 percent of the metered value.

The major features shown in figure 5 are that the NOx levels are low over the range of test conditions and the NOx levels of the 36-point injector are significantly lower than the 25-point injector. With the 36-fuel-injector array, at an inlet temperature of 810 K, inlet pressure of 2760 kPa, pressure drop of 4 percent and a flame temperature of 1900 K, the NOx emission index is less than 6. At the same condition with the 25-fuel-injector array, the NOx emission index ranged between 9 and 11 depending on the swirler.

The lower NOx with the 36-injector array, compared to the 25-injector array, is probably a result of the greater number of smaller mixing sites. The air and fuel are in closer proximity at the module face with the 36-injector array, lessening the effect of large-scale mixing of fuel and air. Another factor is that the flow number (fuel flow rate divided by the square root of the product of injection differential pressure drop and liquid density) for the 25-injector is approximately 1.50 mm^2 while that of the 36-injector array is 1.18 mm^2. Thus for the same fuel flow the 36-injector array requires a factor of 1.6 times more pressure drop than the 25-injector array. From Lefebvre (ref. 10) the effect of fuel-injector pressure drop on mean-drop size is pressure drop to the –0.28 to –0.44 power, which implies that the 36-injector array has a 13 to 19 percent smaller average drop size. Smaller drops vaporize more quickly and mix with the air more

quickly to form less NOx. Conversely, Lefebvre (ref. 11) suggests that an increase in mean-drop size results in some drops burning in an "envelope" flame or local diffusion flame, which results in local regions of high temperature and high NOx.

A higher air-pressure drop through the module also decreases NOx emissions. The higher pressure drop (since the flow area is fixed) is accomplished by increasing the air mass flow and, consequently, the combustion residence time is decreased. If NOx is a linear function of residence time, as given in Anderson (ref. 12), and the residence time and mass flow vary with the square root of pressure drop, then the NOx production varies inversely with the square root of pressure drop. Another effect of higher pressure drop is higher levels of turbulence that increases mixing and decreases NOx production. A third factor is that as the air- pressure drop increases, the air mass flow, and for the same flame temperature, the fuel flow both increase. This in turn increases the fuel pressure drop, resulting in better atomization and a smaller average drop size. Smaller drop size is also a result of enhanced primary and secondary breakup of the fuel stream brought about by the higher air velocity.

For the 25-injector array, the NOx emissions are not a strong function of the swirl number (the swirl number is defined as the tangential momentum divided by axial momentum, Beer and Chigier (ref. 13)). An increase in the swirl number increases the strength of the recirculation zone that probably enhances the mixing of the fuel and air. The swirler configuration with the highest swirl number of 0.8 has lower NOx at lower flame temperatures, but at higher flame temperatures, the NOx for all configurations is approximately the same.

The effect of having the swirl direction alternate within the array, versus all swirl in the same direction, is also small. For the configuration with the air swirlers rotating the flow in opposite directions (counter rotation in the plots), at the point where the flows intersect, the swirl direction is the same. This promotes a strong recirculation zone. For adjacent air swirlers with swirl in the same direction, the flows oppose each other at the point where they interact. In this case, the shear stress and, therefore, turbulence should be higher, making for better mixing. It is thought that this is beneficial in reducing NOx, but the effect of swirl rotation of adjacent swirlers is not strong.

The NOx emissions are shown at low power conditions are shown in figure 5(h). Configuration B is used with only 12 of the 25 fuel injectors flowing fuel. The twelve injectors used were in a alternating or checkerboard pattern. The purpose of using only half of the injectors is to improve the range of good combustion efficiency at the low power conditions (see discussion below on combustion efficiency). As expected the NOx emissions are higher when only twelve fuel injectors are used. For comparison, at an inlet temperature of 590 K and inlet pressure of 930 kPa, an EINOx of 2 occurred at a flame temperature of 1740 K with configuration B and 12 injectors flowing as compared to a flame temperature 1950 K with configuration E and all 36 injectors flowing.

The effect of the inlet conditions, i.e., temperature, pressure, fuel-air ratio, and pressure drop on NOx are correlated in figure 6. The NOx is correlated in two ways. The first uses a standard correlation developed at NASA based on many configurations tested in the Advanced Subsonic Technology Program both from industry and NASA configurations, Wey (ref. 9),

$$EINOx = a_0 * P_3^{0.594} * e^{(T_3/194)} * (FAR)^{1.688} * (\Delta P/P \%)^{-0.565} \qquad (1)$$

The correlation is excellent for the 25-point (Configuration D, fig. 6(b)) but only is fair (regression $R^2 = 0.82$) for the 36-point injector (Configuration E, fig. 6(a)). The second correlation is a fit of the data from the test configurations described in this paper.
For Configuration D

$$EINOx = b_0 * P_3^{0.594} * e^{(T_3/194)} * (FAR)^{2.129} * (\Delta P/P \%)^{-0.565} \qquad (2)$$

For Configuration E

$$EINOx = b_0 * P_3^{0.594} * e^{(T_3/194)} * (FAR)^{3.88} * (\Delta P/P \%)^{-0.565} \qquad (3)$$

The fit is a slight improvement for the 25-point Configuration D but is a significant improvement for the 36-point Configuration E ($R^2 = 0.95$ for both). The effect of inlet temperature, pressure and pressure drop are similar in both correlations and the exponents are in the range of generally accepted values. The effect of fuel-air ratio is greater for the 36-point Configuration E, which suggests that the 36-point configurations are closer to a premixed flame than the 25-point configurations and AST configurations. Using the LDI correlation the characteristic level (DP/F_∞), the parameter obtained by integrating integrates emissions over a landing/takeoff-cycle) is calculated for NOx and compared to the ICAO standards for 55:1 and 30:1 pressure-ratio engines using a hypothetical engine cycle. The numbers are 83 percent below the standards for 36-point configuration. Note that these are based on data from flame-tube experiments and may not be indicative of a real engine.

The combustion efficiency for various conditions is shown in figure 7. For the range of conditions with inlet temperatures between 590 and 810 K, and inlet pressures between 1380 and 2760 kPa, the combustion efficiency is greater than 99.9 percent for flame temperatures above 1600 K. Staging of the fuel injectors was tried at an inlet temperature of 464 K and an inlet pressure of 930 kPa. For this case, 12 of 25 fuel injectors in an alternating pattern were used. For this configuration, an overall fuel-air ratio greater than 0.0397 is required to attain a combustion efficiency greater than 99 percent. This fuel-air ratio is too high for a practical application and indicates the need for increased fuel staging.

Radial profiles of fuel-air ratio, NOx, CO, and combustion efficiency are shown in figure 8 at two axial locations. The radial profile at 10.1 cm is from a vertical traverse and at 15.2 cm, a horizontal traverse. The fuel distribution (as shown by fuel-air ratio) is nearly uniform with a variation about ±10 percent. The distribution is more uniform at the upstream location. The average of the data at the upstream 102 mm location is less than the average value at the 203 mm location, whereas the average value at the 152 mm location is approximately the same as the 203 mm location. The NOx and CO emissions varied in exactly the same way as the fuel distribution, i.e., where the fuel concentration is high the NOx and CO are high. The combustion efficiency varies inversely with CO and is essentially the mirror image of the CO plot.

Summary and Conclusions

A low-NOx, multipoint LDI concept has been demonstrated in flame-tube tests. The configurations tested had 25- and 36-fuel-injector modules in the size of a conventional, single fuel-injector. Each fuel injector had a radial air swirler for quick mixing of the fuel and air before burning. With the 25-fuel-injector array, air-swirler arrays with swirl numbers of 0.5, 0.8, and one with a combination of 0.5 and 0.8 were used. Air-swirler arrays with adjacent co-rotating and counter-rotating swirlers were evaluated. With the 36-fuel-injector array, only the swirler array with the combination of 0.5 and 0.8 swirl numbers was used. An integrated approach was used for the construction of the injector modules where chemically etched laminates were diffusion bonded to combine the fuel injectors, air swirlers and fuel manifold into a single element. Test conditions ranged from inlet temperatures up to 810K, inlet pressures up to 2760 kPa, and flame temperatures up to 2100 K. The NOx levels were quite low at all conditions. With the 36-fuel-injector array, at an inlet temperature of 810 K, inlet pressure of 2760 kPa, pressure drop of 4 percent and a flame temperature of 1900 K, the NOx emission index was less than 6. At the same condition with the 25-fuel-injector array, the NOx emission index was between 9 and 11. The difference in emission index for the various swirler arrays was insignificant.

A correlation was developed relating the NOx emission index to inlet temperature, inlet pressure, fuel-air ratio and pressure drop. The correlation had the usual dependence on inlet pressure and pressure

drop, but the effect of fuel-air ratio was greater than is usually reported and more similar to that of a premixed combustor. Assuming that 10 percent of the combustion air would be used for liner cooling (compared to 30 percent in a conventional combustor), in a typical engine cycle, the NOx emission index from the correlation was estimated to be less than 20 percent of the 1996 ICAO standard. Note that these are based on data from flame-tube experiments and may not be indicative of a real engine. Further research is needed for application to a real engine.

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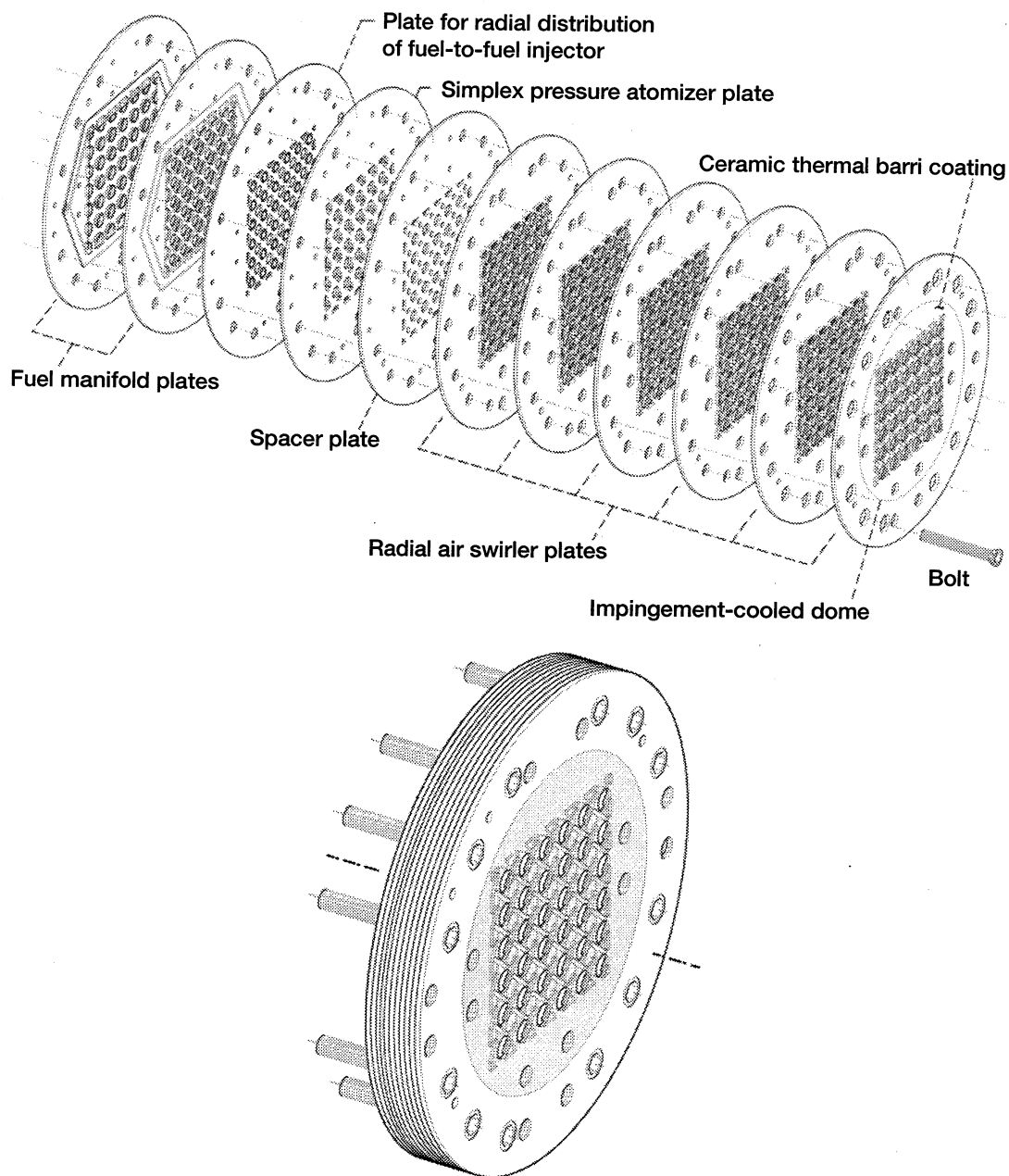13. Beer and Chigier, 1972, *Combustion Aerodynamics*, John Wiley & Sons.

Figure 1.—Multipoint integrated module. (a) Etched plates. (b) Flame-tube configuration.

Radial air swirler

Combustion air

Fuel manifold

Simplex pressure atomizer

Fuel spray

Fuel-air mixture

Combustion air

Ceramic thermal coating

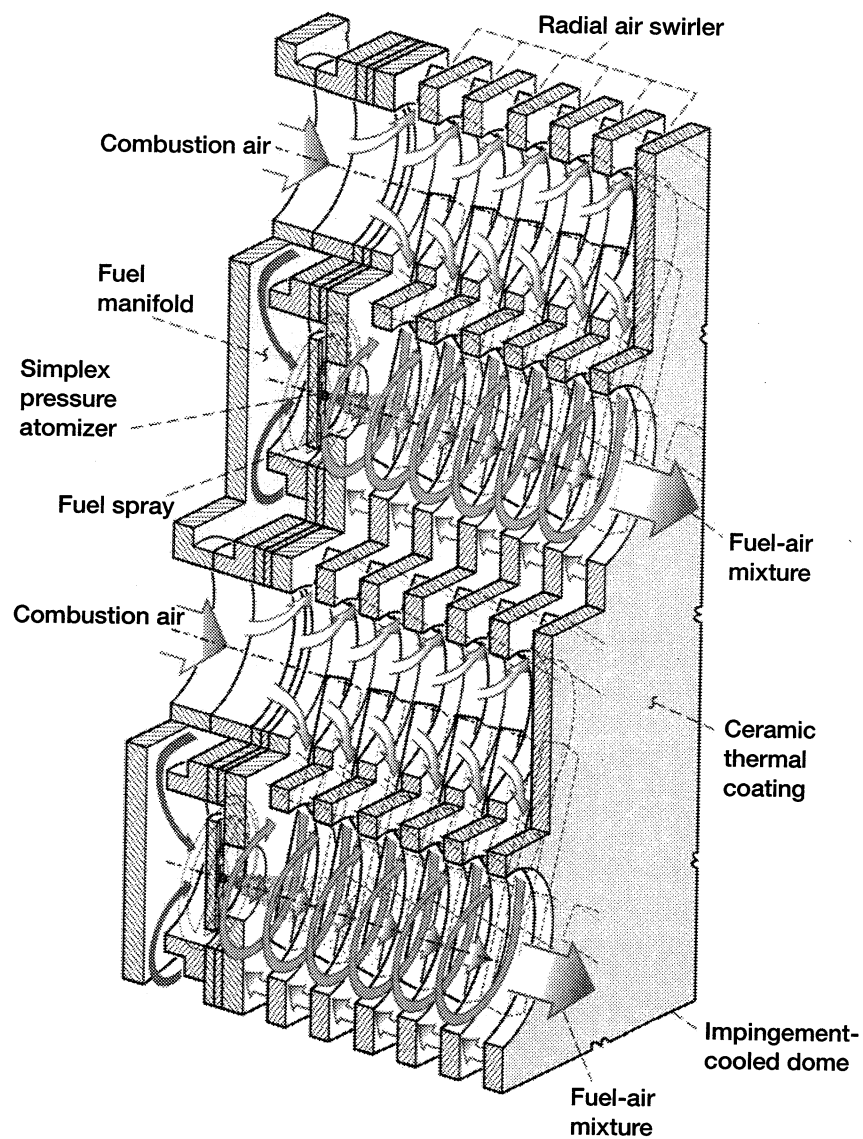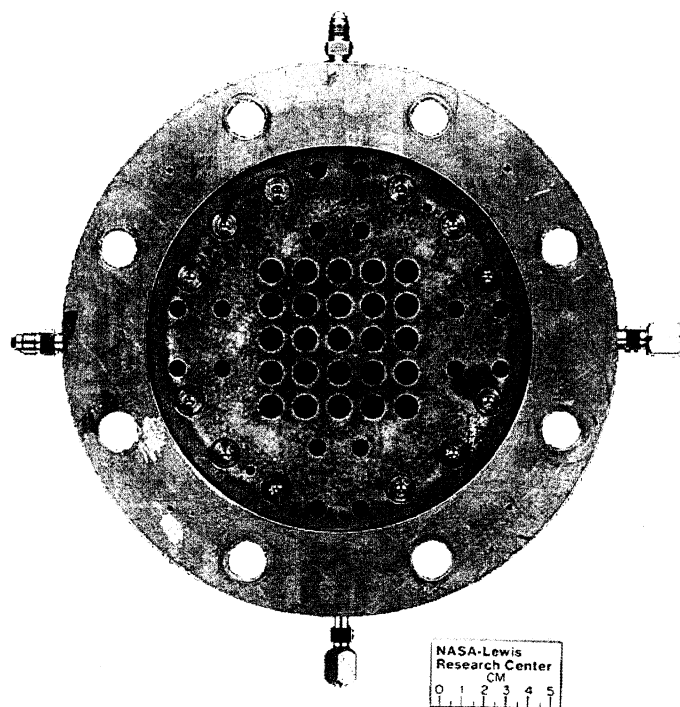Impingement-cooled dome

Fuel-air mixture

Figure 2.—Fuel and air flow detail.

Figure 3.—Photograph of flame-tube assembly.
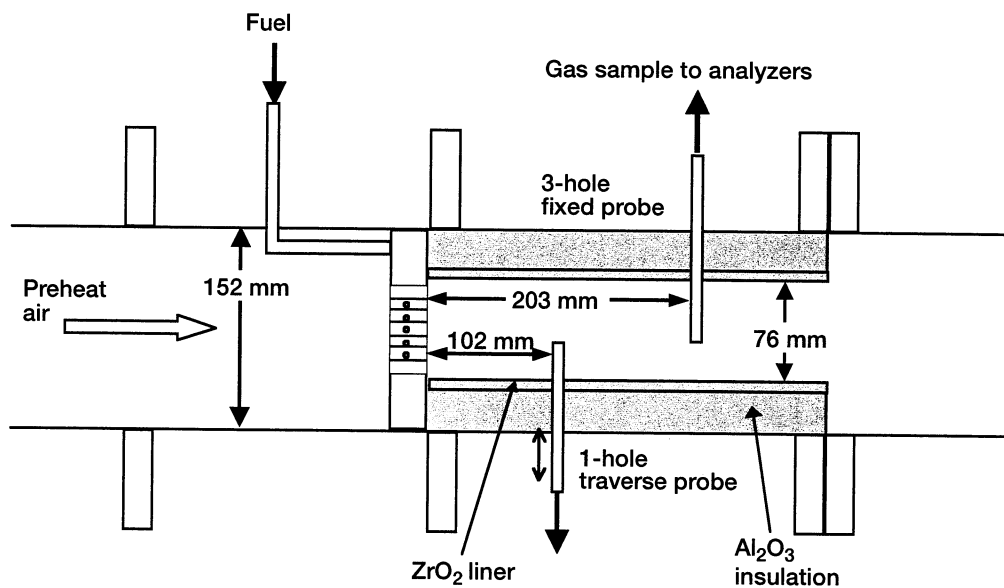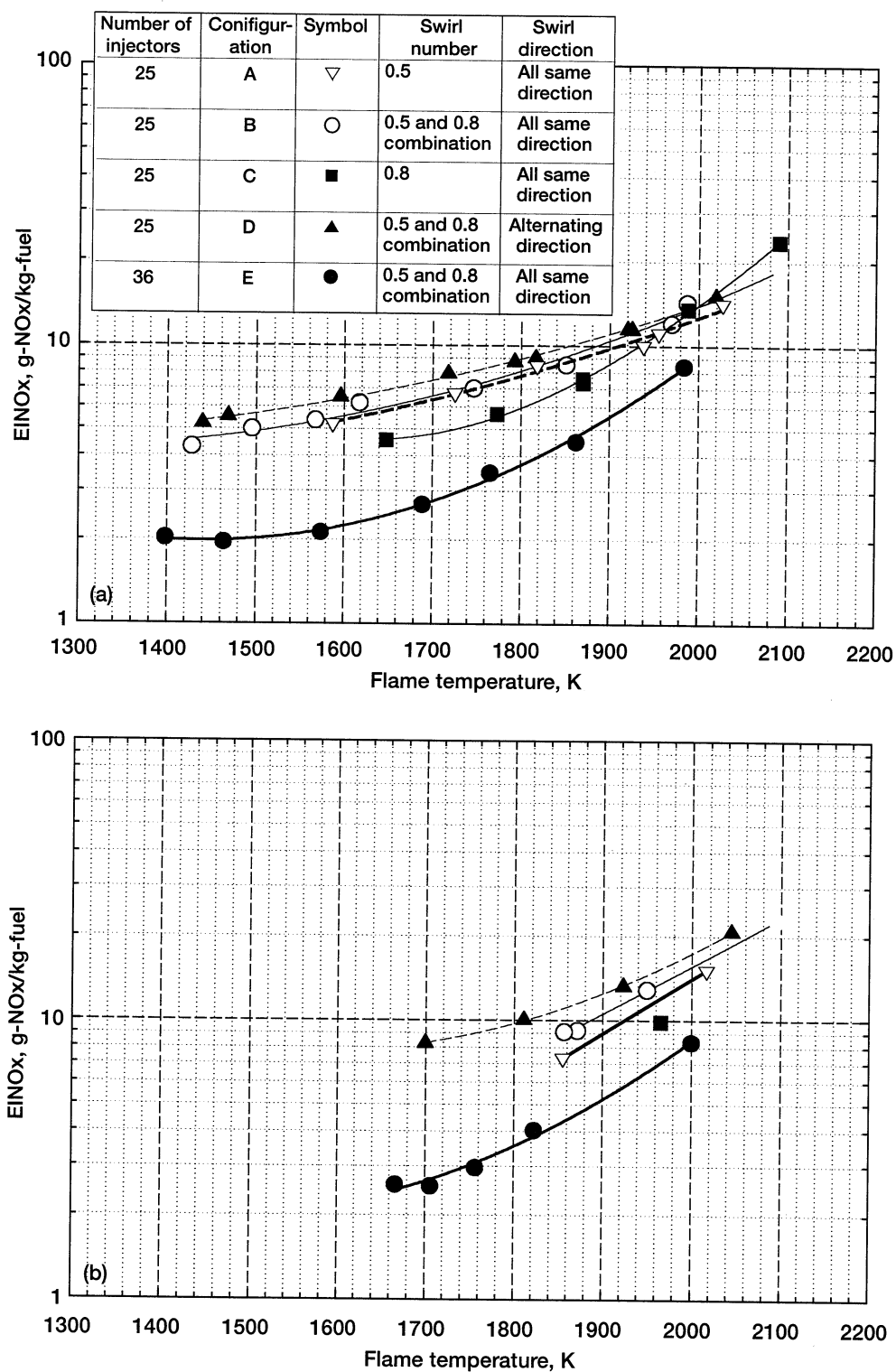

Figure 4.—Experimental test facility.

Number of injectors	Conifigur- ation	Symbol	Swirl number	Swirl direction
25	A	▽	0.5	All same direction
25	B	○	0.5 and 0.8 combination	All same direction
25	C	■	0.8	All same direction
25	D	▲	0.5 and 0.8 combination	Alternating direction
36	E	●	0.5 and 0.8 combination	All same direction

Figure 5.—NOx emissions index as function of flame temperature for each configuration at various conditions. (a) T_3 = 810 K, P_3 = 2760 kPa, $\Delta P/P_3$ = 4%. (b) T_3 = 810 K, P_3 = 1380 kPa, $\Delta P/P_3$ = 4%.

Number of injectors	Configuration	Symbol	Swirl number	Swirl direction
25	A	▽	0.5	All same direction
25	B	○	0.5 and 0.8 combination	All same direction
25	C	■	0.8	All same direction
25	D	◀	0.5 and 0.8 combination	Alternating direction
36	E	●	0.5 and 0.8 combination	All same direction
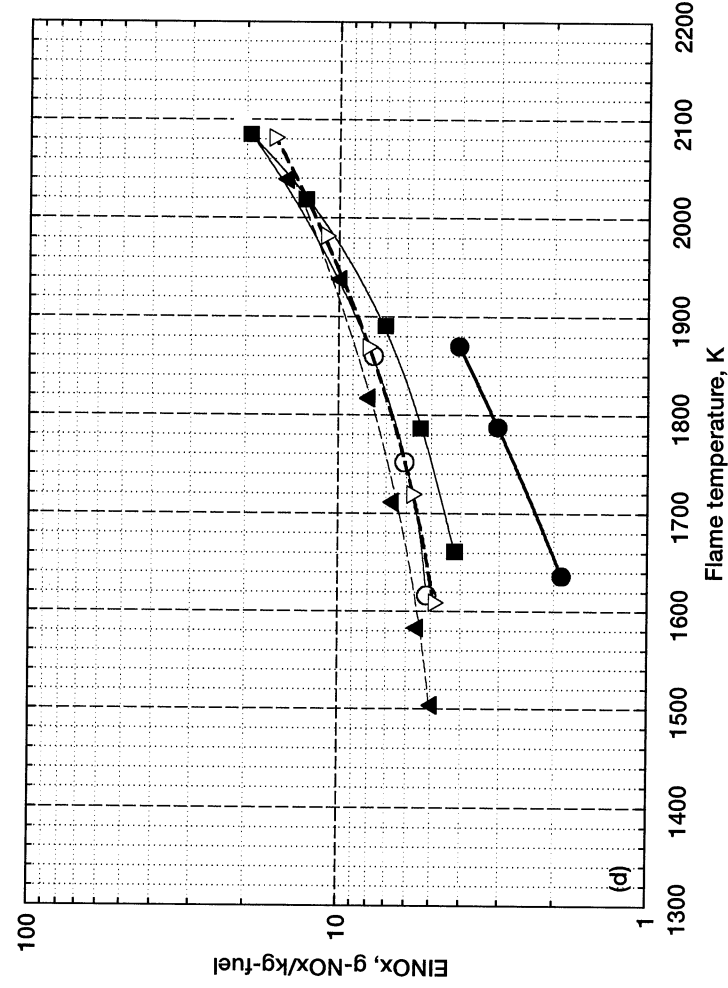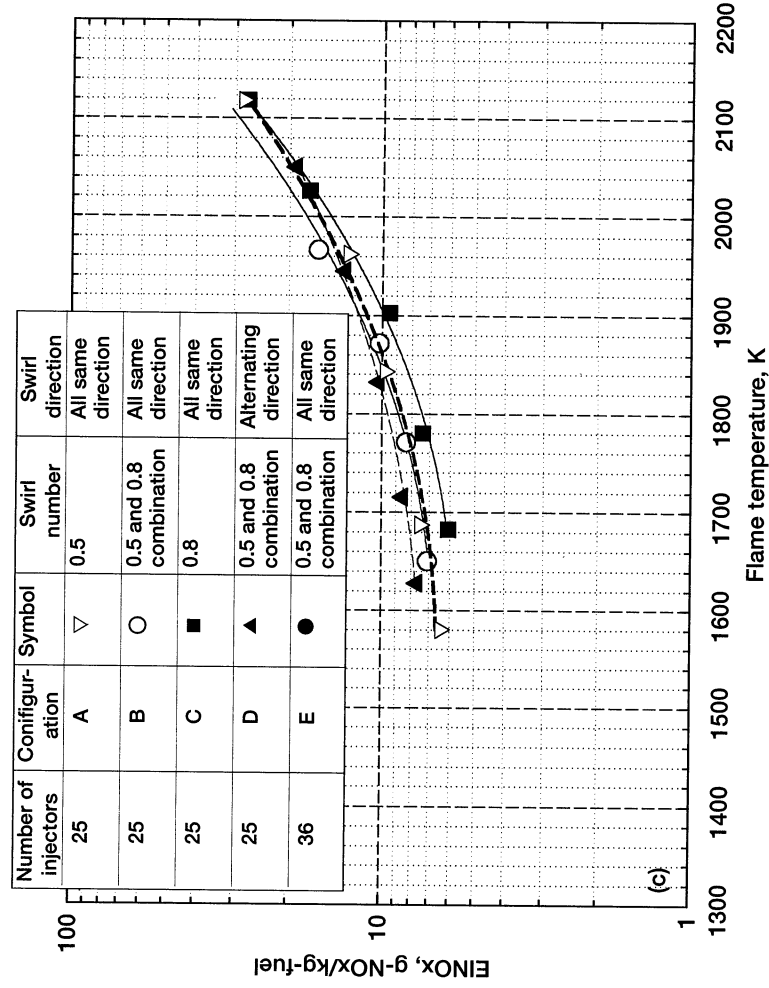
Figure 5.—Continued. (c) T_3 = 810 K, P_3 = 2760 kPa, $\Delta P/P_3$ = 3%. (d) T_3 = 810 K, P_3 = 2760 kPa, $\Delta P/P_3$ = 5%.
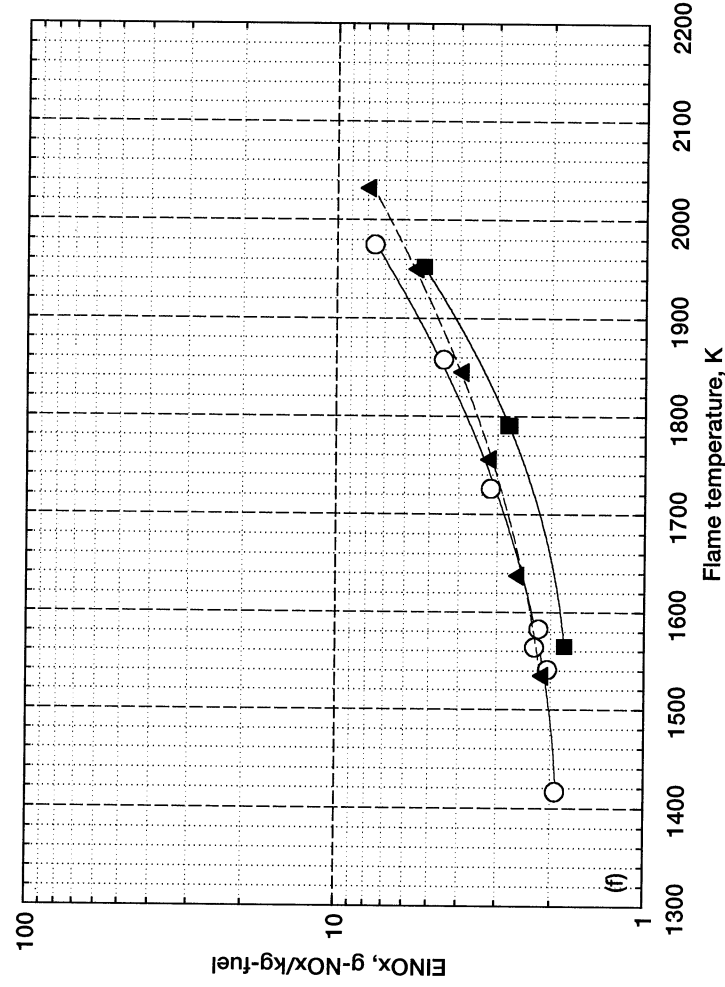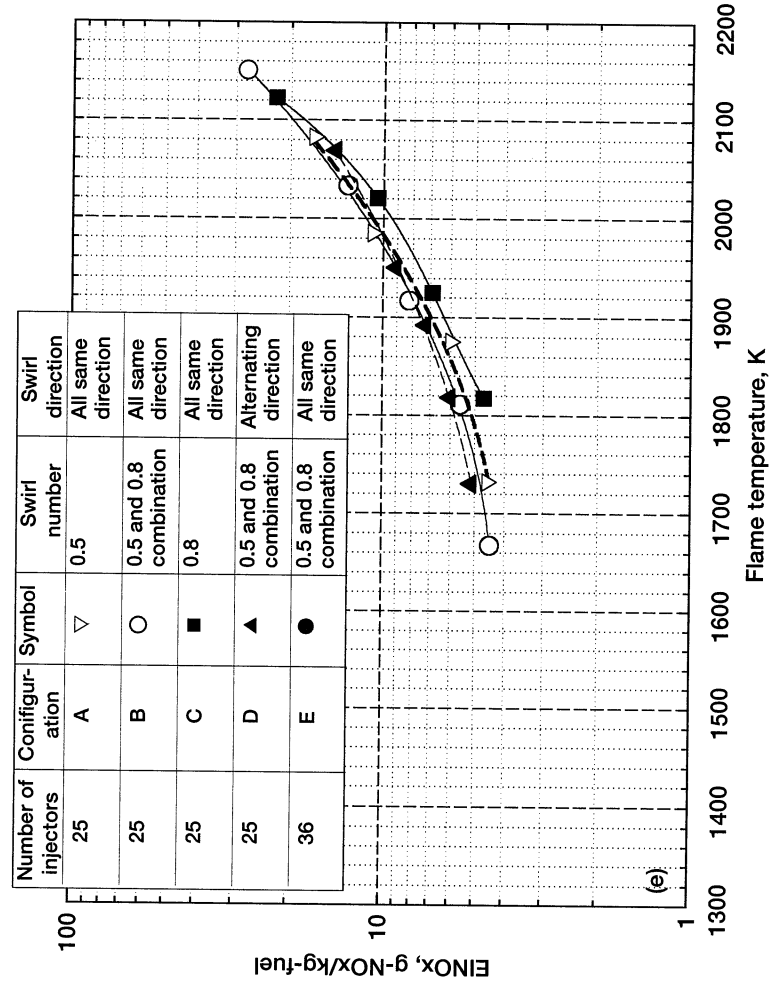
Figure 5.—Continued. (e) $T_3 = 700$ K, $P_3 = 2760$ kPa, $\Delta P/P_3 = 4\%$. (f) $T_3 = 590$ K, $P_3 = 2760$ kPa, $\Delta P/P_3 = 4\%$.
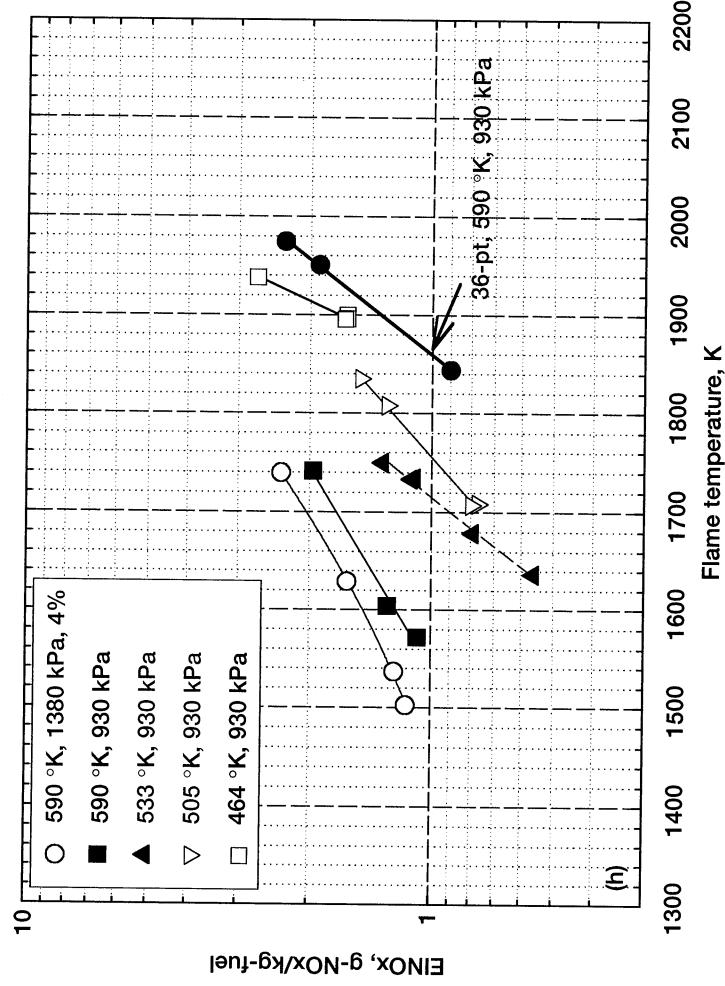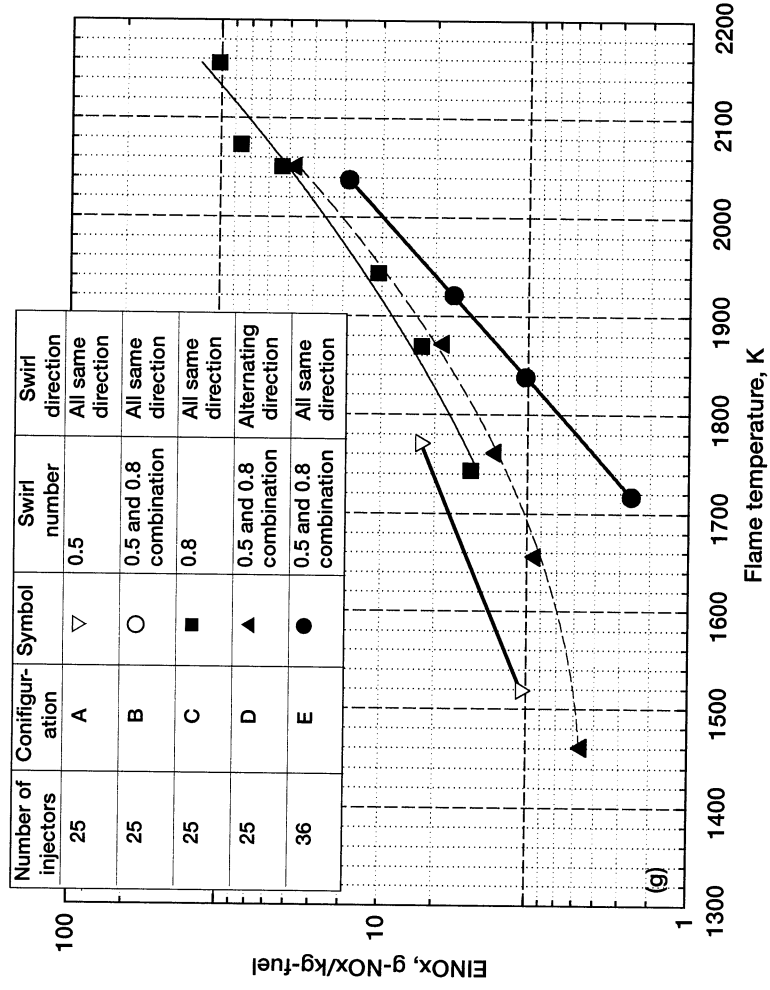
(g)

Number of injectors	Configur-ation	Symbol	Swirl number	Swirl direction
25	A	▽	0.5	All same direction
25	B	○	0.5 and 0.8 combination	All same direction
25	C	■	0.8	All same direction
25	D	▲	0.5 and 0.8 combination	Alternating direction
36	E	●	0.5 and 0.8 combination	All same direction

EINOx, g-NOx/kg-fuel

Flame temperature, K

(h)

○ 590 °K, 1380 kPa, 4%
■ 590 °K, 930 kPa
▲ 533 °K, 930 kPa
▽ 505 °K, 930 kPa
□ 464 °K, 930 kPa

36-pt, 590 °K, 930 kPa

EINOx, g-NOx/kg-fuel

Flame temperature, K

Figure 5.—Concluded. (g) T_3 = 590 K, P_3 = 1380 kPa, $\Delta P/P_3$ = 4%. (h) One fuel circuit of configuration B.

$+$ EINOx $= 805 \; {}^* P_3^{0.594} \; {}^* \exp(T_3/194) \; {}^* (FAR)^{3.88} \; {}^*(\Delta P/P \; \%)^{-0.565}$

$\square$ EINOx $= 0.52 \; {}^* P_3^{0.594} \; {}^* \exp(T_3/194) \; {}^* (FAR)^{1.688} \; {}^*(\Delta P/P \; \%)^{-0.565}$

$+$ EINOx $= 4.64 \; {}^* P_3^{0.594} \; {}^* \exp(T_3/194) \; {}^* (FAR)^{2.129} \; {}^*(\Delta P/P \; \%)^{-0.565}$

$\square$ EINOx $= 1.10 \; {}^* P_3^{0.594} \; {}^* \exp(T_3/194) \; {}^* (FAR)^{1.688} \; {}^*(\Delta P/P \; \%)^{-0.565}$
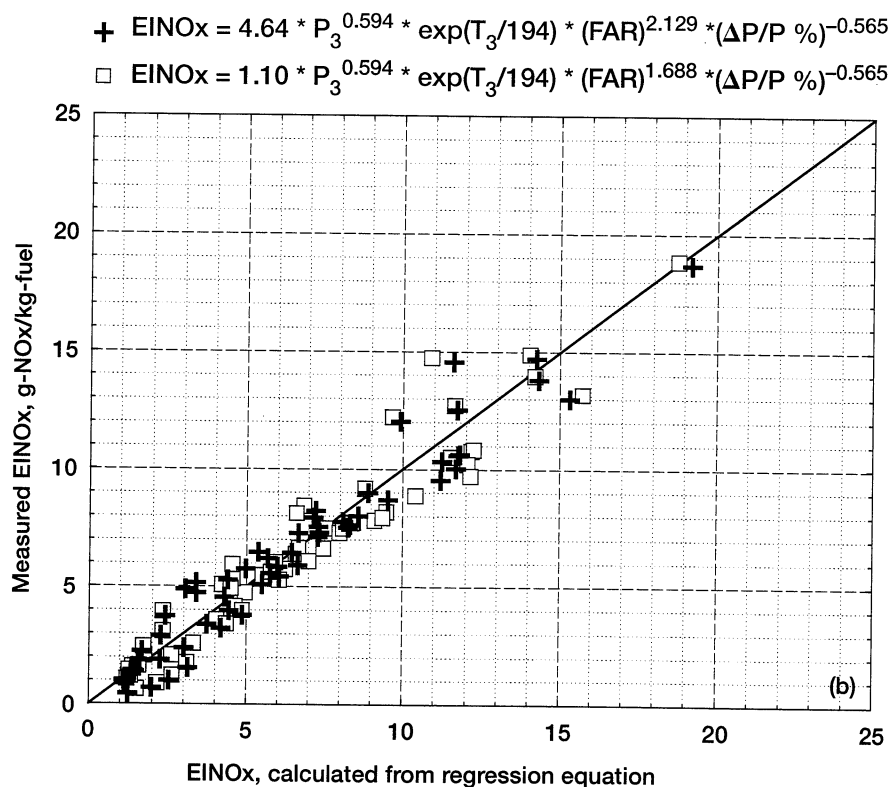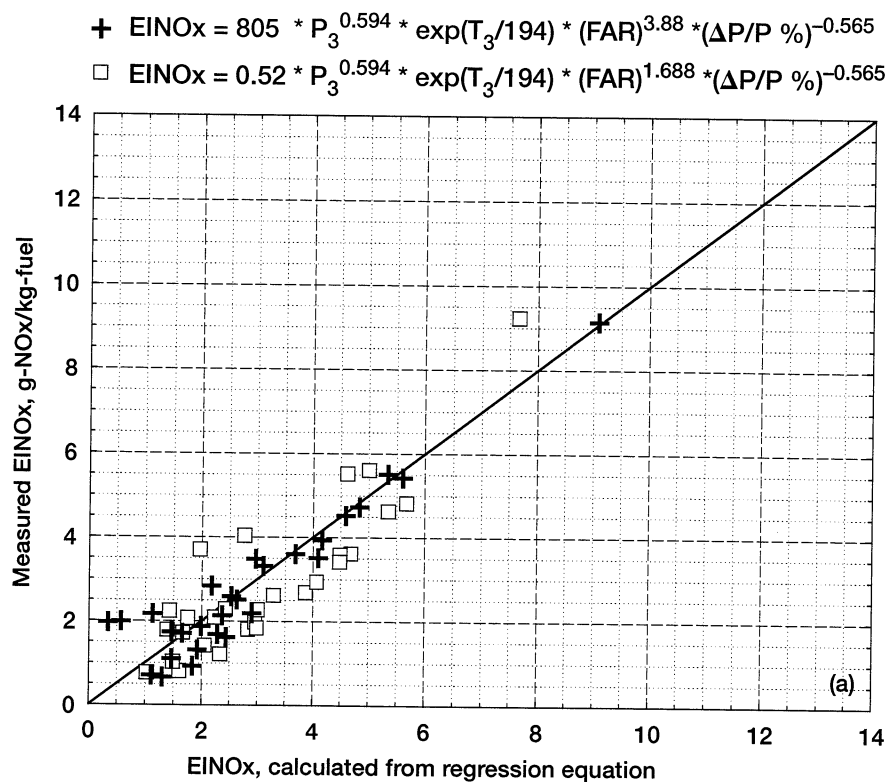
Figure 6.—EINOx regression. (a) Configuration E. (b) Configuration D.
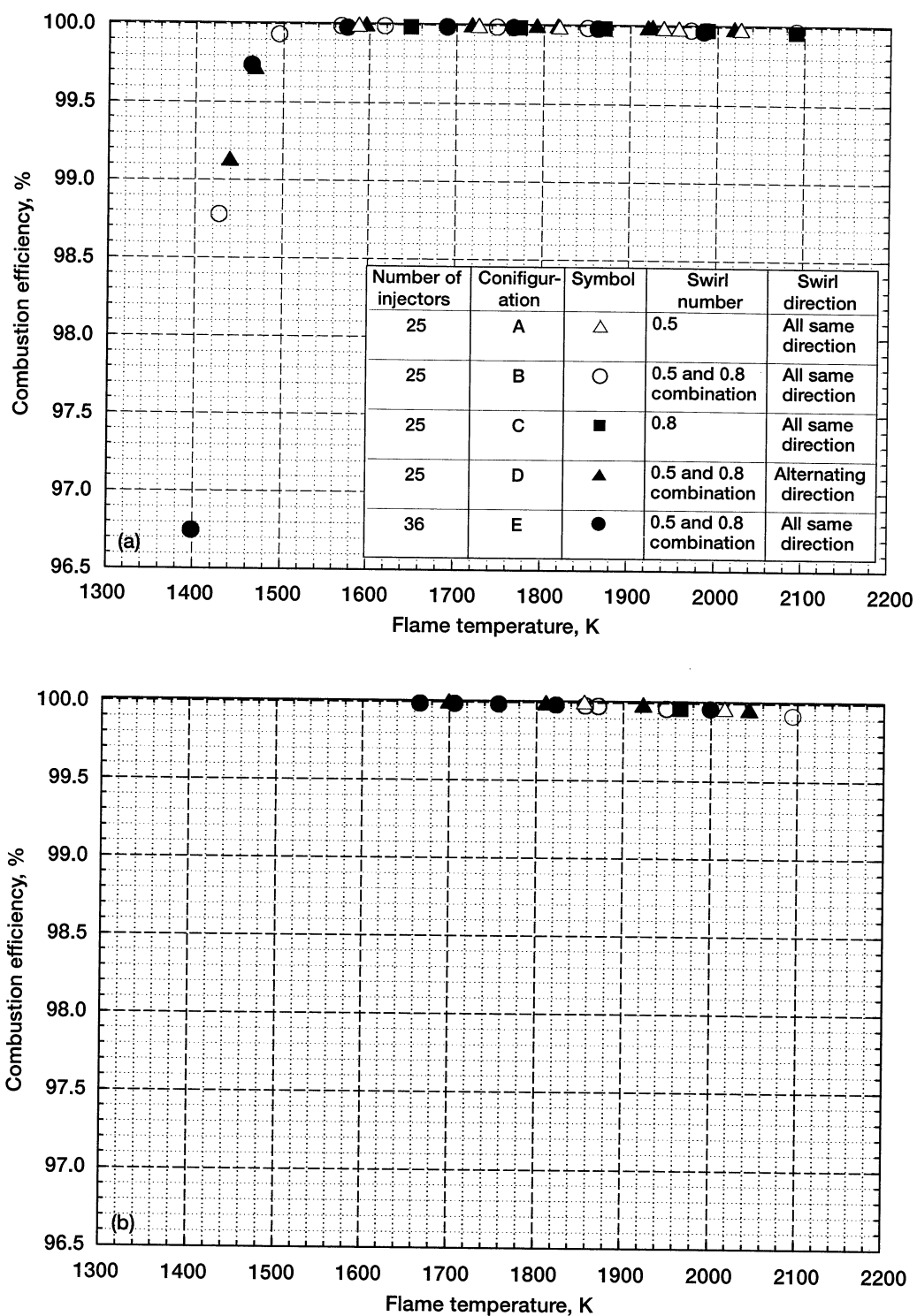
Figure 7.—Combustion efficiency versus flame temperature for each configuration at various conditions. (a) T_3 = 810 K, P_3 = 2760 kPa, $\Delta P/P_3$ = 4%. (b) T_3 = 810 K, P_3 = 1380 kPa, $\Delta P/P_3$ = 4%.
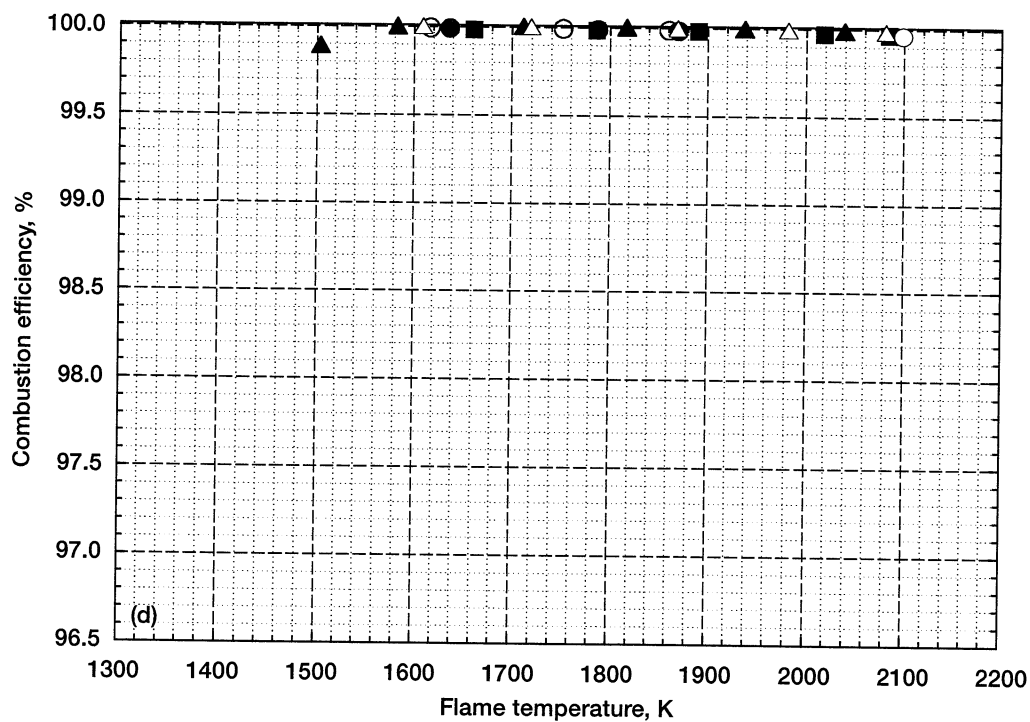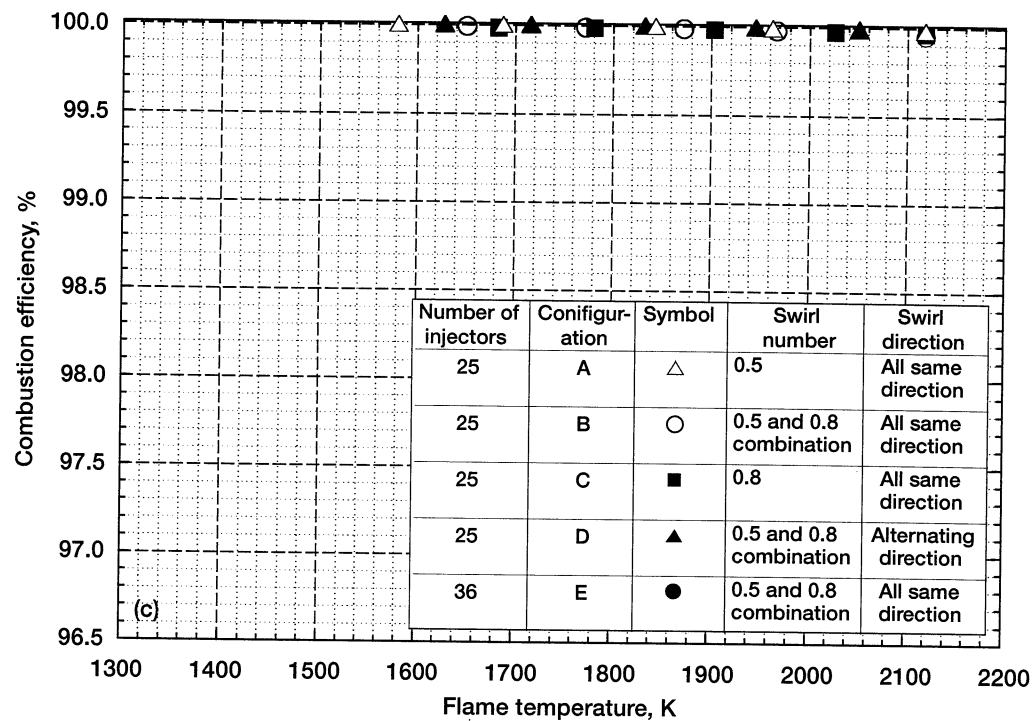
Figure 7.—Continued. (c) $T_3 = 810$ K, $P_3 = 2760$ kPa, $\Delta P/P_3 = 3\%$. (d) $T_3 = 810$ K, $P_3 = 2760$ kPa, $\Delta P/P_3 = 5\%$.

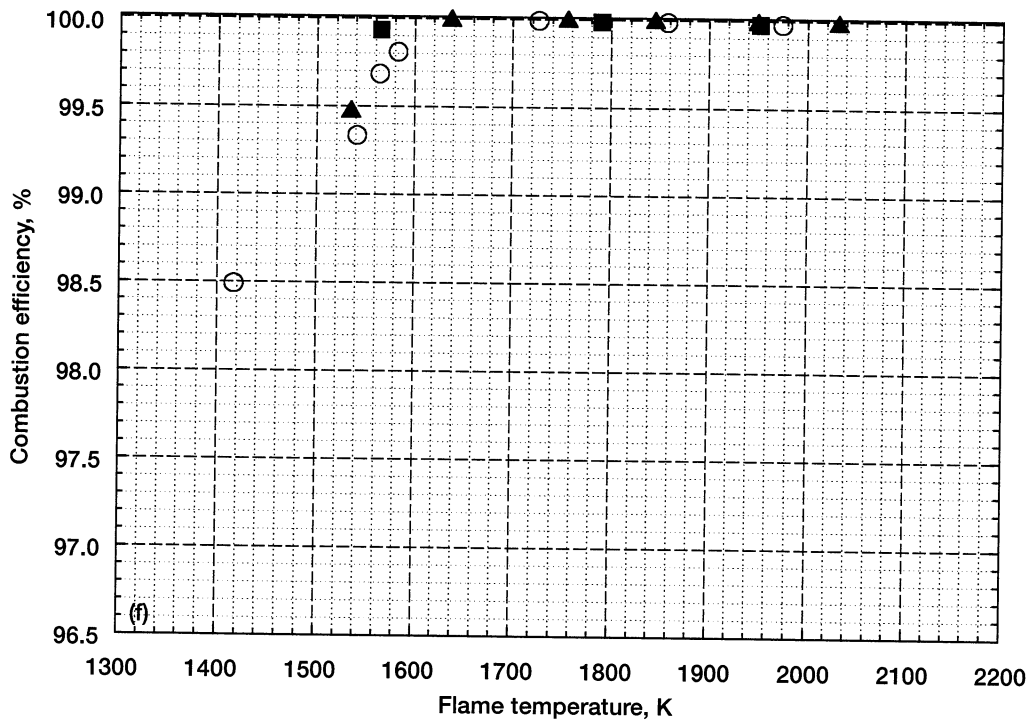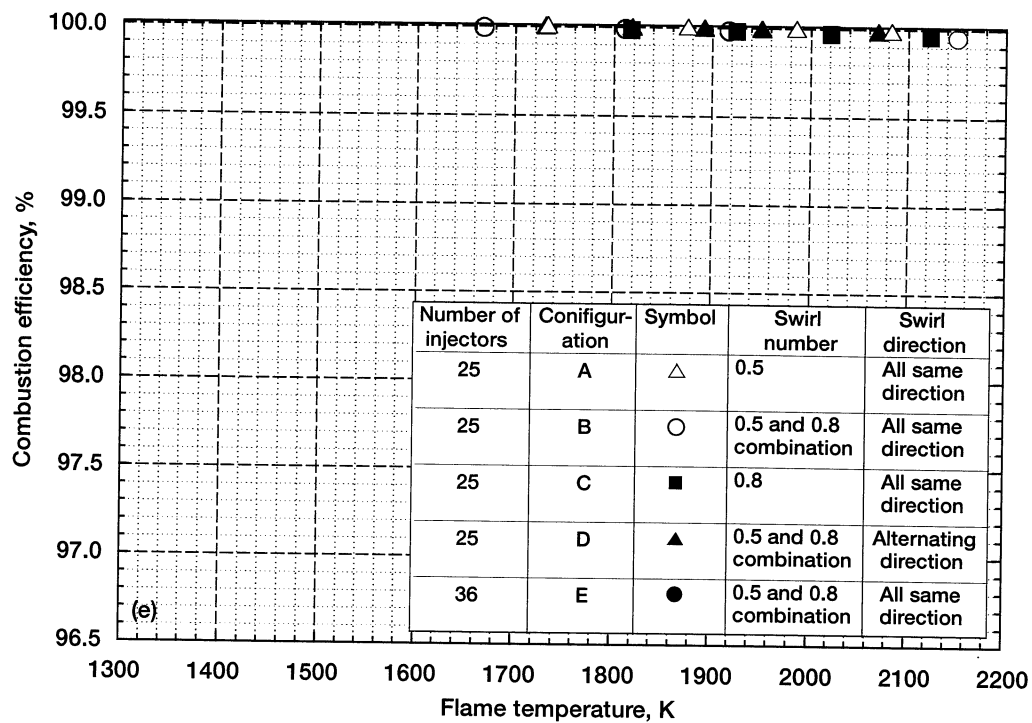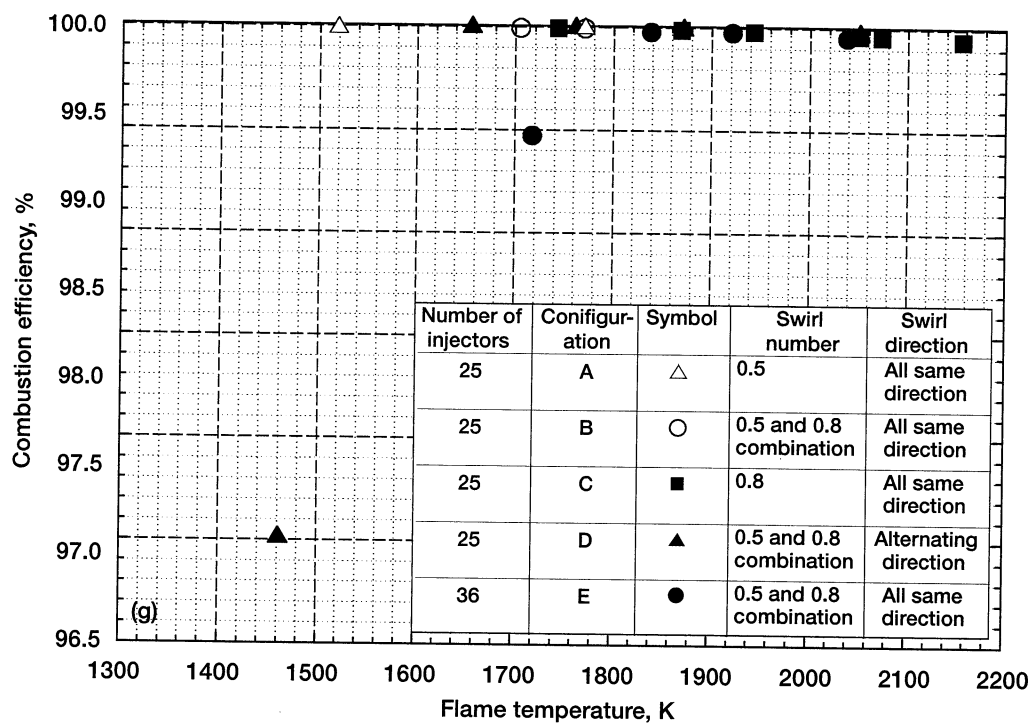| Number of injectors	Conifigur-ation	Symbol	Swirl number	Swirl direction
25	A	△	0.5	All same direction
25	B	○	0.5 and 0.8 combination	All same direction
25	C	■	0.8	All same direction
25	D	▲	0.5 and 0.8 combination	Alternating direction
36	E	●	0.5 and 0.8 combination	All same direction

Figure 7.—Continued. (e) $T_3 = 700$ K, $P_3 = 2760$ kPa, $\Delta P/P_3 = 4\%$. (f) $T_3 = 590$ K, $P_3 = 2760$ kPa, $\Delta P/P_3 = 4\%$.

Number of injectors	Conifigur- ation	Symbol	Swirl number	Swirl direction
25	A	△	0.5	All same direction
25	B	○	0.5 and 0.8 combination	All same direction
25	C	■	0.8	All same direction
25	D	▲	0.5 and 0.8 combination	Alternating direction
36	E	●	0.5 and 0.8 combination	All same direction

Figure 7.—Concluded. (g) T_3 = 590 K, P_3 = 1380 kPa, $\Delta P/P_3$ = 4%.
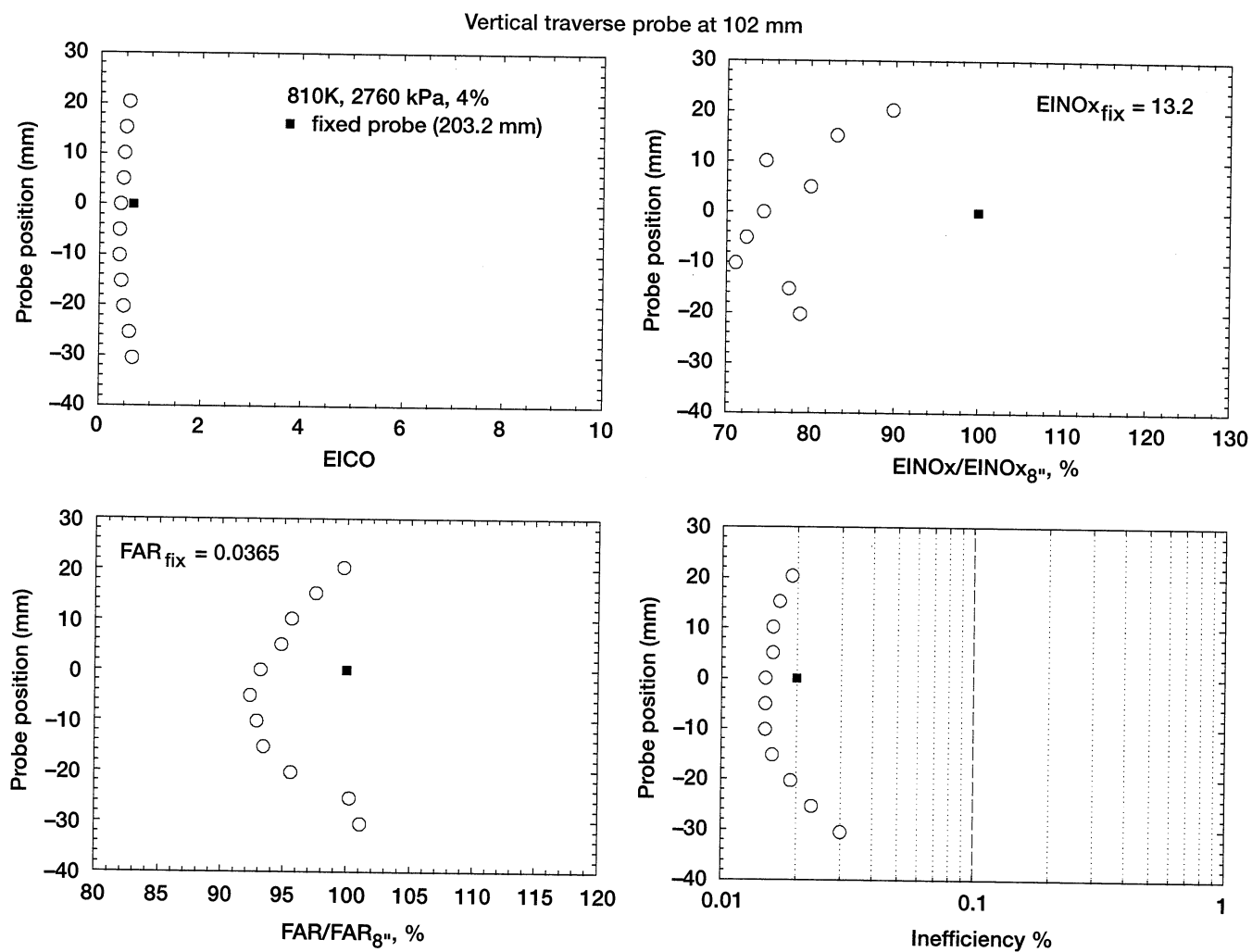
Figure 8.—Emission profiles. (a) Configuration B at 102 mm.
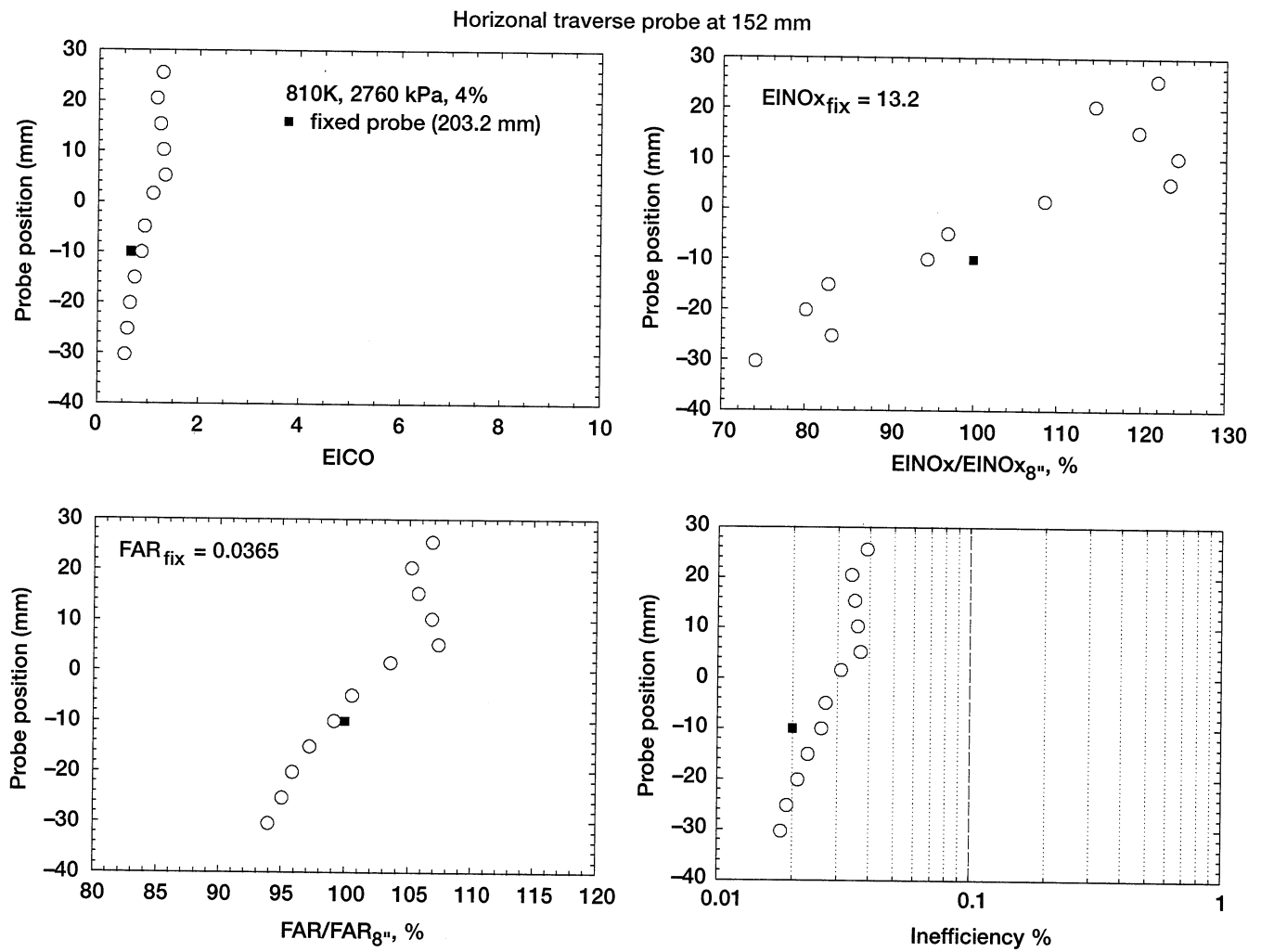
Figure 8.—(b) Configuration B at 152 mm.

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13. ABSTRACT (Maximum 200 words)

A low NOx emissions combustor has been demonstrated in flame-tube tests. A multipoint, lean-direct injection concept was used. Configurations were tested that had 25- and 36- fuel injectors in the size of a conventional single fuel injector. An integrated-module approach was used for the construction where chemically etched laminates, diffusion bonded together, combine the fuel injectors, air swirlers and fuel manifold into a single element. Test conditions were inlet temperatures up to 810 K, inlet pressures up to 2760 kPa, and flame temperatures up to 2100 K. A correlation was developed relating the NOx emissions with the inlet temperature, inlet pressure, fuel-air ratio and pressure drop. Assuming that 10 percent of the combustion air would be used for liner cooling and using a hypothetical engine cycle, the NOx emissions using the correlation from flame-tube tests were estimated to be less than 20 percent of the 1996 ICAO standard.

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Combustor; NOx emissions; Lean-direct-injection; Fuel injection

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